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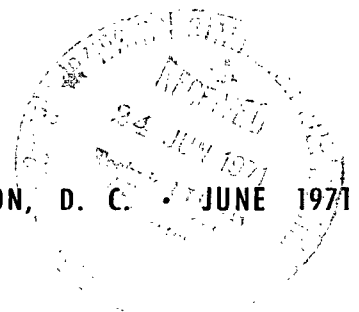


# **FRICITION AND WEAR OF SINTERED TUNGSTEN, MOLYBDENUM, AND COBALT-MOLYBDENUM IMPREGNATED WITH A FLUORIDE EUTECTIC**

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16. Abstract <p>A friction and wear study was conducted in an argon atmosphere on self-lubricating composites made of porous metals (44 percent dense) and 38-wt%CaF<sub>2</sub> - 62-wt%BaF<sub>2</sub> eutectic. The metals used were tungsten, molybdenum, and an alloy of 75-wt% cobalt - 25-wt% molybdenum. Each proved to be a suitable matrix material for the fluoride lubricant. The best results were obtained with the filled Co-25Mo composite. The metal alloy and fluoride filler in this composite seemed to be of mutual benefit in providing a lower friction coefficient over a wider range of temperature. At a sliding velocity of 2.6 meters per second the friction coefficient was 0.35 at ambient temperatures and dropped off linearly to 0.10 at 900° C. Wear was not markedly affected by temperature; and the wear rate was three orders of magnitude lower than was obtained in control tests with denser, unlubricated tungsten, molybdenum, and Co-25Mo.</p>			
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# FRICTION AND WEAR OF SINTERED TUNGSTEN, MOLYBDENUM, AND COBALT-MOLYBDENUM IMPREGNATED WITH A FLUORIDE EUTECTIC

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## SUMMARY

Friction and wear characteristics were determined for dense metallic riders sliding on self-lubricating composite disks. The composites consisted of porous molybdenum, porous tungsten, or porous 75-weight-percent cobalt - 25-weight-percent molybdenum metals which were impregnated with a calcium fluoride - barium fluoride eutectic mixture (38-wt%  $\text{CaF}_2$  - 62-wt%  $\text{BaF}_2$ ). The porous metal matrix was 44 percent dense, except for one case where 22-percent-dense tungsten was used.

A hemispherically tipped rider (0.476-cm radius) generated a 5-centimeter-diameter wear track on the flat surface of the 6.3-centimeter-diameter disk. A 1-kilogram load was applied to the rider and the disk was rotated at 1000 rpm; this gave the rider a linear sliding speed of 2.6 meters per second (520 ft/min) relative to the disk. All tests were conducted in a dry, nonoxidizing atmosphere of argon.

The results indicate that the composites functioned as good friction and wear reducers up to a temperature of about 900<sup>0</sup> C. Above 900<sup>0</sup> C the  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic became very soft, and plastic deformation of the composite ensued. The friction coefficient decreased linearly with temperature increase, but a comparison of rider wear scars at 25<sup>0</sup> and 900<sup>0</sup> C indicated that temperature did not markedly affect wear.

Cobalt-molybdenum composites proved to be superior to the others in both friction and wear reduction. A cast 65-weight-percent cobalt - 25-weight-percent molybdenum - 10-weight-percent chromium rider gave better results on this material than did a cast molybdenum rider. A tungsten rider sliding on a 22-percent-dense tungsten disk which was filled with the  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic gave low friction and low rider wear. However, high wear of the composite material occurred.

## INTRODUCTION

It has been shown in previous Lewis research (ref. 1) that lubrication at high tem-

peratures can be achieved with self-lubricating composites of sintered nickel-base alloys impregnated with a calcium fluoride - barium fluoride ( $\text{CaF}_2$ - $\text{BaF}_2$ ) eutectic. Other investigators (refs. 2 to 5) have found that cobalt and cobalt-base alloys have very good friction and wear properties as long as the material maintains a hexagonal-close-packed (hcp) structure.

The transformation of cobalt from hcp to face-centered-cubic (fcc) structure is complex, since the transformation is time dependent as well as temperature dependent (refs. 6 to 13). Various investigators (refs. 6 to 13) have found values for the transformation temperature ranging from  $390^\circ$  to  $460^\circ$  C. When friction is involved, the transformation temperature in vacuum is reduced to about  $290^\circ$  C (refs. 4 and 5). In references 4 and 5, it is also shown that the presence of 25-weight-percent molybdenum (Mo) in cobalt (Co) inhibits the hcp-to-fcc crystal transformation, and thus the hcp structure is maintained to higher temperatures.

Since this alloy of cobalt and molybdenum exhibits low friction and low wear in the unlubricated condition, it is of interest to determine whether there are advantages for using it as a sintered metal matrix material for  $\text{CaF}_2$ -based lubricants. Composites made of this nongalling metal and a high-temperature lubricant could have improved lubricating properties.

For high-temperature applications, beyond the temperature limits of nickel (Ni) and cobalt alloys, refractory metals such as tungsten (W) and molybdenum are of interest. Because of their poor oxidation resistance, applications for these metals must be restricted to nonoxidizing atmospheres.

In this investigation, lubrication with composites of sintered molybdenum and of sintered tungsten, both infiltrated with  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic, was studied. The eutectic melts at  $1022^\circ$  C ( $1872^\circ$  F), thus the usefulness of the composites is limited to temperatures below this melting point. However, experiments with this eutectic can demonstrate whether Mo and W are suitable metals for use in self-lubricating composites. For lubrication at higher temperatures, fillers such as 100-weight-percent  $\text{CaF}_2$  (melting point,  $1418^\circ$  C or  $2584^\circ$  F) could be used. Other possibilities are the rare earth fluorides, such as lanthanum fluoride (melting point,  $1490^\circ$  C or  $2714^\circ$  F), which were shown to be effective at high temperatures (ref. 14).

This study was conducted (1) to investigate the possibility that a composite of Co-25Mo and  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic would function as a good self-lubricating material and (2) to determine if Mo and W are suitable matrix metals for fluoride-metal self-lubricating composites.

## FRICION AND WEAR APPARATUS

The device used in this investigation to measure friction and wear is illustrated in

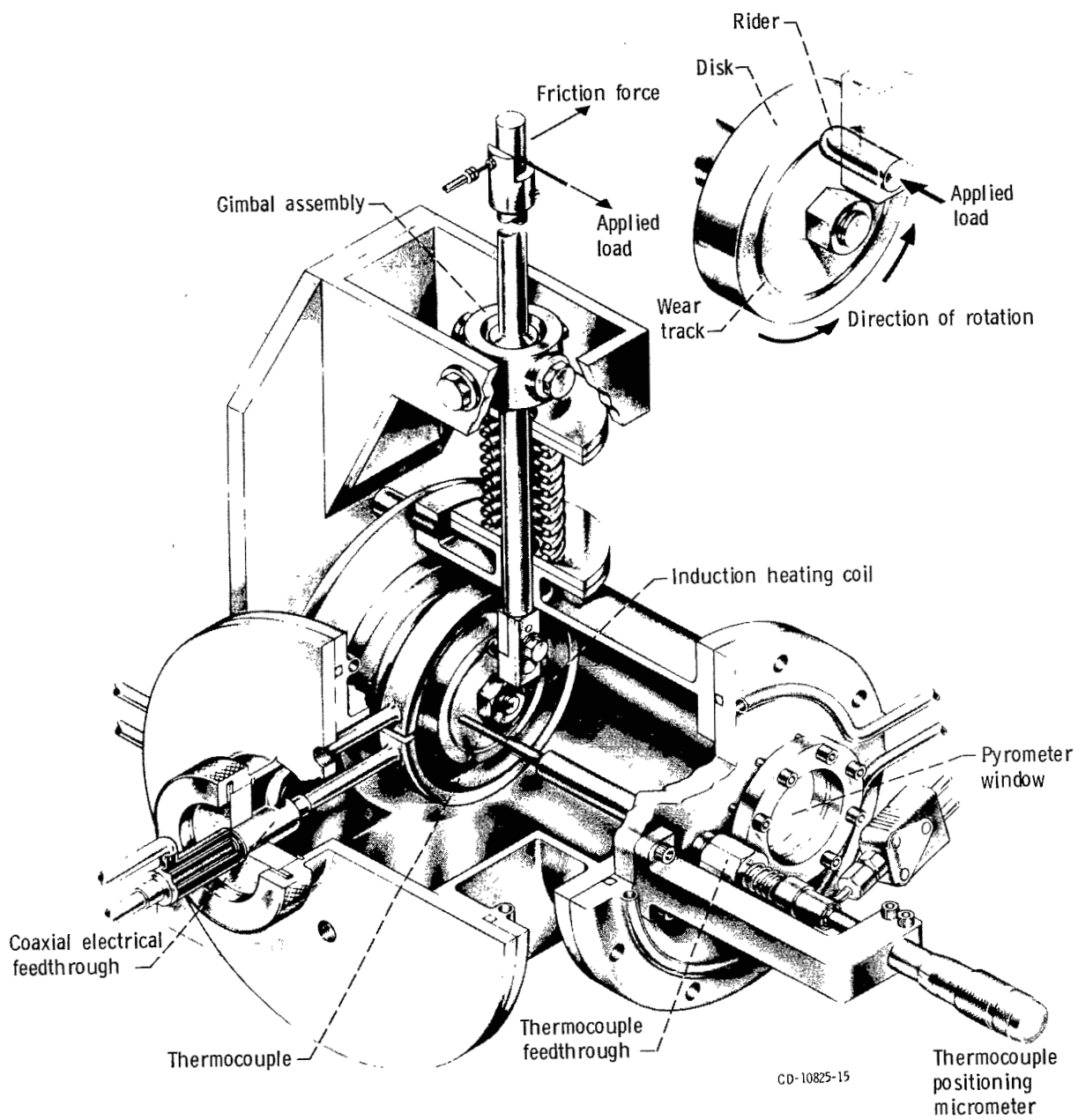


Figure 1. - Friction and wear testing device.

figure 1. Basically, the device consists of a flat (6.3-cm-diameter) disk in sliding contact with a stationary (0.476-cm-radius) hemispherically tipped rider. The disk is rotated at 1000 rpm and a 1-kilogram load is applied to the rider. The rider slides on a 5-centimeter-diameter circular track on the disk, thus giving it a linear sliding speed of 2.6 meters per second relative to the disk.

Induction heating is used to heat the disk. This is accomplished by placing an induction coil around the circumferential surface of the disk. When the disk is stationary, the temperature is monitored by a Chromel-Alumel thermocouple. A micrometer is employed to move the thermocouple away from the disk surface before it is set in motion. The temperature is then monitored by an infrared optical pyrometer which is focused on the wear track of the disk.

A strain gage is used to measure the frictional forces, which are continuously recorded on a strip-chart recorder.

## TEST SPECIMENS

Three different rider materials were used in this study: arc-cast tungsten, molybdenum, and an alloy of 65-weight-percent cobalt - 25-weight-percent molybdenum - 10-weight-percent chromium (Co-25Mo-10Cr). Tungsten, molybdenum, and an alloy of 75-weight-percent cobalt - 25-weight-percent molybdenum (Co-25Mo) were used to make the porous metal disks.

The disks were obtained from a commercial source and were prepared by standard powder-metallurgy techniques. The size of the powders used in making them ranged from 60 to 105 micrometers in diameter. Disks with two different metallic densities were made: 44 and 22 percent. The resulting material is foam-like in structure and has a range of pore sizes. The pores are irregular in shape with typical pore dimensions from 15 to 60 micrometers for the 44-percent-dense disks and from 20 to 70 micrometers for the 22-percent-dense disks.

A  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic composition (38-wt%  $\text{CaF}_2$  - 62-wt%  $\text{BaF}_2$ ) was used as the lubricant and was infiltrated by vacuum impregnation into the disks at 1100° C. The infiltration procedure is given in reference 1.

Some disks made of 100-percent-dense tungsten, molybdenum, and Co-25Mo were also used. These disks were run unlubricated.

Some physical properties of tungsten, molybdenum, and cobalt are listed in table I (refs. 7 and 8). The Rockwell hardness of the test specimens is listed in table II.

TABLE I. - PHYSICAL PROPERTIES OF TUNGSTEN,  
MOLYBDENUM, AND COBALT

Property	W	Mo	Co
Atomic weight	183.92	95.95	58.94
Atomic number	74	42	27
Density at 20° C, g/cm <sup>3</sup>	19.3	10.2	8.9
Melting point, °C	3410	2610	1493
Lattice type	bcc	bcc	hcp (fcc above 417° C)
Coefficient of linear expansion, mean value from 20° to 500° C, per °C	$5.0 \times 10^{-6}$	$5.2 \times 10^{-6}$	$14 \times 10^{-6}$
Thermal conductivity, cal/ (cm <sup>3</sup> )(°C)(sec)	0.31	0.28	0.16
Specific heat, cal/(g)(°C)	0.032	0.065	0.106

TABLE II. - ROCKWELL HARDNESS OF TEST SPECIMENS

Specimen	Material			
	Co-25Mo-10Cr	Co-25Mo	Mo	W
Rider	R <sub>C</sub> -52	-----	R <sub>B</sub> -93	R <sub>C</sub> -25
100-Percent-dense disk	-----	R <sub>C</sub> -53	R <sub>B</sub> -94	R <sub>C</sub> -28
44-Percent-dense disk (38CaF <sub>2</sub> -62BaF <sub>2</sub> filled)	-----	R <sub>B</sub> -90 to R <sub>B</sub> -96	R <sub>B</sub> -73 to R <sub>B</sub> -83	R <sub>B</sub> -80 to R <sub>B</sub> -87
22-Percent-dense disk (38CaF <sub>2</sub> -62BaF <sub>2</sub> filled)	-----	-----	-----	R <sub>B</sub> -60 to R <sub>B</sub> -65

## CLEANING PROCEDURE

The composite disks were scrubbed with a brush under running water in order to remove any loose particles. They were further cleaned with ethyl alcohol and then rinsed with distilled water.

The riders were scrubbed with alcohol. A water paste of levigated alumina was then applied with a clean, white polishing cloth. Cleaning continued until no trace of sediment from the rider appeared on the cloth. A final rinse using distilled water followed. The riders and disks were allowed to dry in a desiccator. The 100-percent-dense disks were cleaned by the same method as the riders.

## TEST PROCEDURE

The specimens were evaluated in the friction apparatus shown in figure 1. Dry argon (moisture content, 10 ppm) was purged through the chamber for 1 hour prior to commencing the tests. The flow rate of the argon was 1500 cubic centimeters per minute. This flow rate maintained a slight positive pressure in the chamber which had a volume of 2000 cubic centimeters.

The first tests performed on the composites were temperature cycle tests. This was done in order to obtain the friction coefficient over a range of temperatures and to determine the upper temperature limitation of the composites.

The tests consisted of a series of runs on the same wear track at 25<sup>o</sup>, 100<sup>o</sup>, 200<sup>o</sup> C, etc., up to 900<sup>o</sup> C. Before commencing a run, the desired temperature was held for 10 minutes to allow it to stabilize. The disk was then set into rotation and the load applied. The run was allowed to continue until the friction coefficient stabilized at a constant value. The load was then removed and rotation stopped. The temperature was raised to the next desired value and this procedure was repeated.

The wear rate was determined at 25<sup>o</sup> C (room temperature) and at 900<sup>o</sup> C by running 1-hour tests and measuring the ensuing wear scar diameter on the hemispherically tipped riders. Wear volume per hour was then calculated from this diameter. Surface profiles of each disk wear track were taken and compared. The friction coefficients were also recorded in these tests.

For a comparison, the wear rate and the friction coefficient of similar dense, unlubricated metals were determined at 25<sup>o</sup> C and at 900<sup>o</sup> C by the same procedure. Since the wear with these dense metals was great, tests of only 2-minute duration were performed. Wear volume per hour was then calculated by extrapolation, assuming the wear rate to be constant.

## RESULTS AND DISCUSSION

### Frictional Behavior

In order to determine the upper temperature lubrication limit of the composites being studied, a series of temperature cycle tests were performed. These tests are described in more detail in the procedure section of this report. The data obtained are presented in figures 2 to 6. Here the mean friction coefficients are plotted as a function of temperature. Also presented are data from tests run on similar metal combinations, but in an unlubricated condition. Dense metal disks were used for these unlubricated tests. The friction coefficient for the unlubricated condition was very erratic; thus,



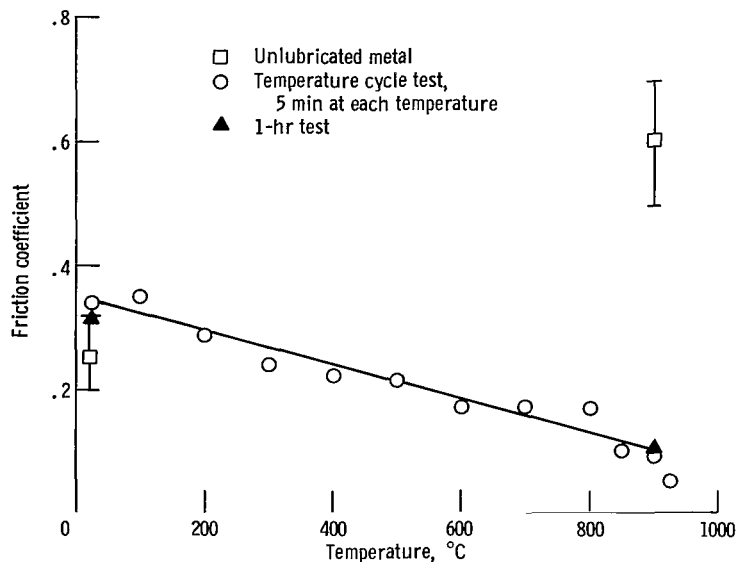


Figure 2. - Friction coefficient as function of temperature for a Co-25Mo-10Cr rider sliding on a 44-percent-dense Co-25Mo disk filled with 38CaF<sub>2</sub>-68BaF<sub>2</sub> eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

a range for the friction coefficient in this case is presented.

Figure 2 gives the results for cast Co-25Mo-10Cr riders sliding on a porous (44-percent dense) Co-25Mo metal disk. The disk is filled with a 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic composition, which served as the solid lubricant in the composite.

The tests were conducted in a nonoxidizing atmosphere of argon. At a sliding velocity of 2.6 meters per second the friction coefficient at room temperature (25° C) was 0.35 and decreased linearly with increasing temperature. At 900° C its value was 0.10. This is a rate of decrease in the friction coefficient of about 0.1 for every 350° C increase in temperature. When the temperature was further increased to 925° C, the friction coefficient dropped to 0.05. The test was terminated at this temperature because the eutectic became soft and severe plastic deformation of the composite disk occurred. Thus, all ensuing tests were terminated at 900° C. Additional tests were conducted at 25° and 900° C using dense unlubricated Co-25Mo disks. These tests were performed in order to compare the friction coefficients of the lubricated and unlubricated materials.

When the two are compared, it is seen that at room temperature (25° C) the mean friction coefficient of the composite material was 0.35, while that of the dense unlubricated Co-Mo metal was 0.25. At 900° C, the mean friction coefficient of the composite was 0.10, while that of the dense unlubricated Co-Mo was 0.6. The CaF<sub>2</sub>-base lubricants have not been used with this particular metal combination before, but it has been reported (ref. 17) that the friction coefficient of CaF<sub>2</sub>-BaF<sub>2</sub> bonded to various metal

surfaces is approximately 0.4 (or higher) at 25° C and less than 0.1 at 900° C. Thus, it seems likely the friction coefficient of the composite is a combination of the Co-25Mo and CaF<sub>2</sub>-BaF<sub>2</sub> eutectic friction coefficients. At room temperature the Co-Mo metal helped reduce the friction coefficient of the composite, while at 900° C the friction coefficient of the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic mixture was the dominating influence. The two materials in combination thus seem to be of mutual benefit in providing a lower friction coefficient over a wider range of temperatures.

Additional tests on the Co-25Mo composites were conducted using arc-cast Mo riders instead of Co-25Mo-10Cr riders. The results are given in figure 3. With Mo riders the

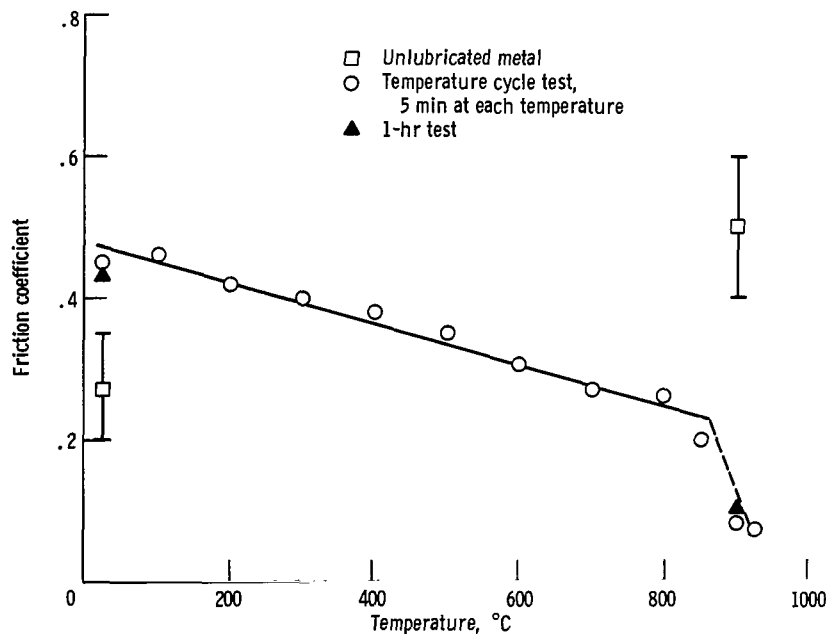


Figure 3. - Friction coefficient as function of temperature for an arc-cast molybdenum rider sliding on a 44-percent-dense Co-25Mo disk impregnated with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

friction coefficient decreases at the same rate (0.1 per 350° C rise in temperature), but at any one specific temperature the friction coefficient is 0.13 higher. At about 850° C the friction coefficient deviates from linearity and drops to a value of 0.08 at 900° C, a value that is close to that obtained when the Co-25Mo-10Cr riders were used.

Molybdenum riders were also run on dense Co-25Mo in the unlubricated condition. The mean friction coefficient recorded at room temperature was 0.27, while at 900° C it was 0.50. This can be compared to the values obtained with the composite disks, which were 0.47 and 0.08 at 25° and 900° C, respectively.

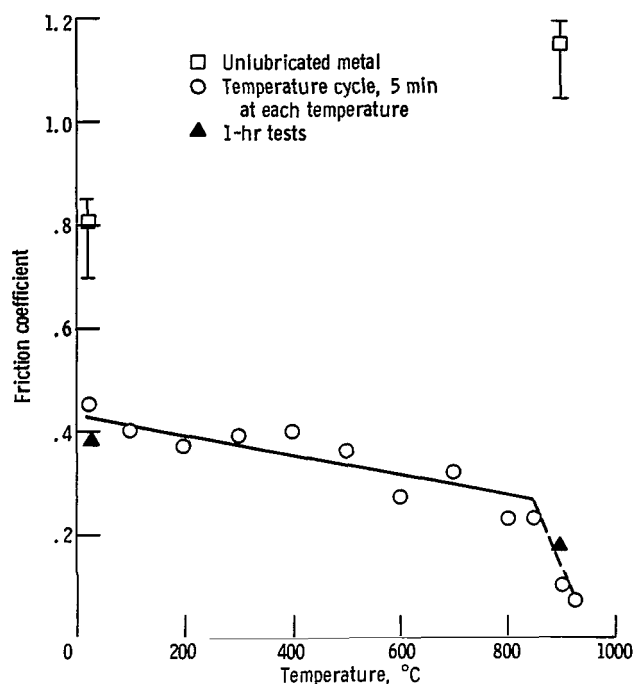


Figure 4. - Friction coefficient as function of temperature for an arc-cast molybdenum rider sliding on a 44-percent-dense molybdenum disk filled with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

The composite material again seemed to give improved results over a wide temperature range; however, the results were not as good as those obtained when the Co-25Mo-10Cr riders were used.

Figure 4 gives the results for arc-cast Mo riders sliding on 44-percent-dense Mo disks filled with the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic mixture. The friction coefficients were somewhat more scattered than those obtained with the Co-25Mo composites, but they still seemed to decrease in a linear manner with an increase in temperature. The rate of decrease is a little less (0.07 per 350° C rise in temperature). The friction coefficient at 25° C is about 0.43, while at 850° C it is 0.27; softening of the Mo composite again occurred at about 900° C and the friction coefficient fell to 0.10.

For the unlubricated, arc-cast Mo rider sliding on a dense Mo disk, the friction was 0.8 at 25° C and 1.15 at 900° C. Thus, the friction coefficient is reduced markedly by using the composite molybdenum rather than the dense metal. These results, however, are still inferior to those obtained when using the Co-25Mo composites.

Figure 5 presents the friction coefficients for an arc-cast W rider sliding on a porous 44-percent-dense W disk filled with the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic. As with the other composite disks the friction coefficient decreases linearly with temperature increase.

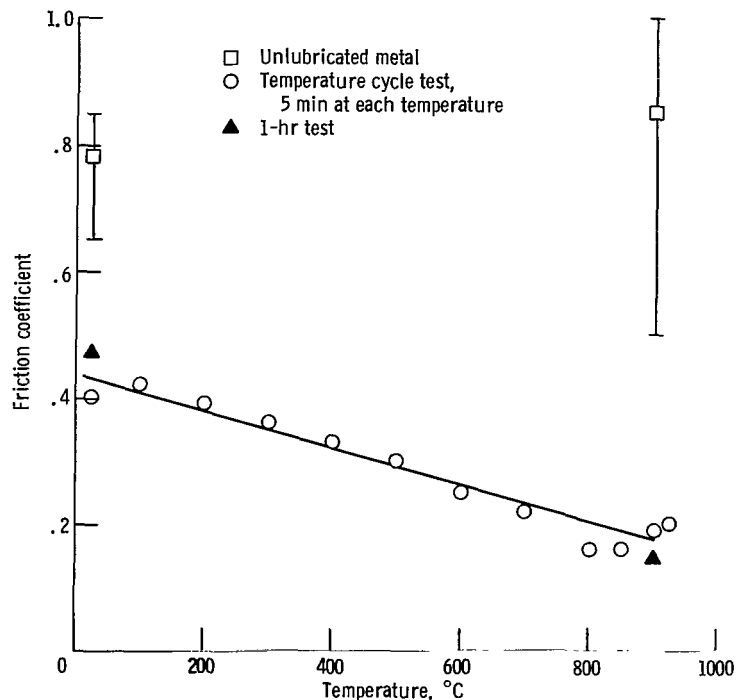


Figure 5. - Friction coefficient as function of temperature for a tungsten rider sliding on a 44-percent-dense tungsten disk filled with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

The rate is (0.1 per 350° C rise in temperature) with values of 0.43 at 25° C and 0.17 at 900° C.

In contrast to the other composite materials, a decrease in the friction coefficient with the tungsten composite did not occur above 900° C. In fact, there seemed to be a slight rise in friction coefficient on further increasing the temperature. For example, the friction coefficient at 925° C is 0.20.

The friction coefficients of the dense W metal sliding in unlubricated contact were very erratic. The mean value at 25° C was 0.78, while that at 900° C was 0.85.

Some additional tests were performed using arc-cast W riders and 22-percent-dense porous W filled with the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic. The purpose of these tests was to see if the lower density material would function adequately as a matrix material for the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic. Figure 6 gives the friction data obtained from these tests. It is seen that the friction coefficients are about 0.05 lower than those obtained using the 44-percent-dense disks. However, it is observed that the 22-percent-dense composite deforms more than a 44-percent-dense composite. Above 850° C, the friction coefficient rises with temperature, as was observed with the 44-percent-dense tungsten; however, in this case it is more pronounced.

A comparison of the mean friction coefficients as a function of temperature (for each

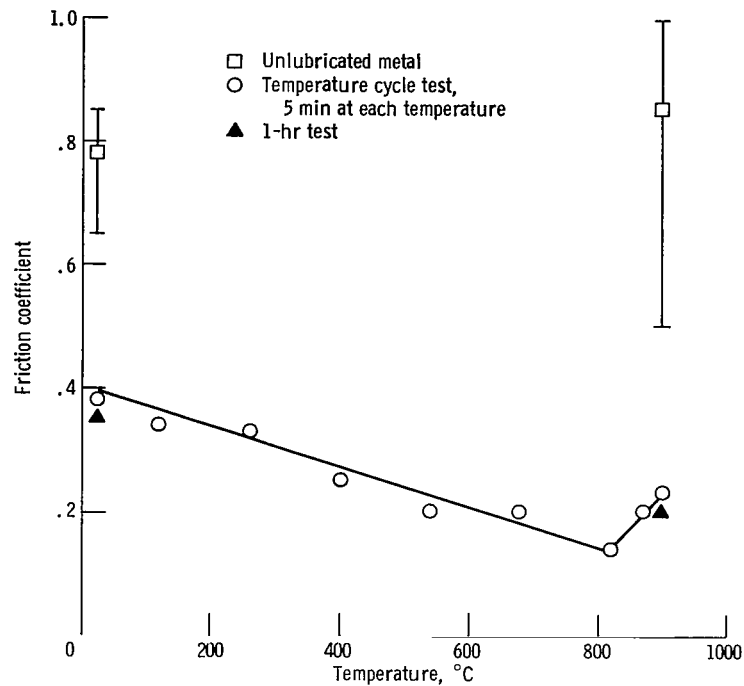


Figure 6. - Friction coefficient as function of temperature for a tungsten rider sliding on a 22-percent-dense tungsten disk filled with  $38\text{CaF}_2$ - $62\text{BaF}_2$  eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

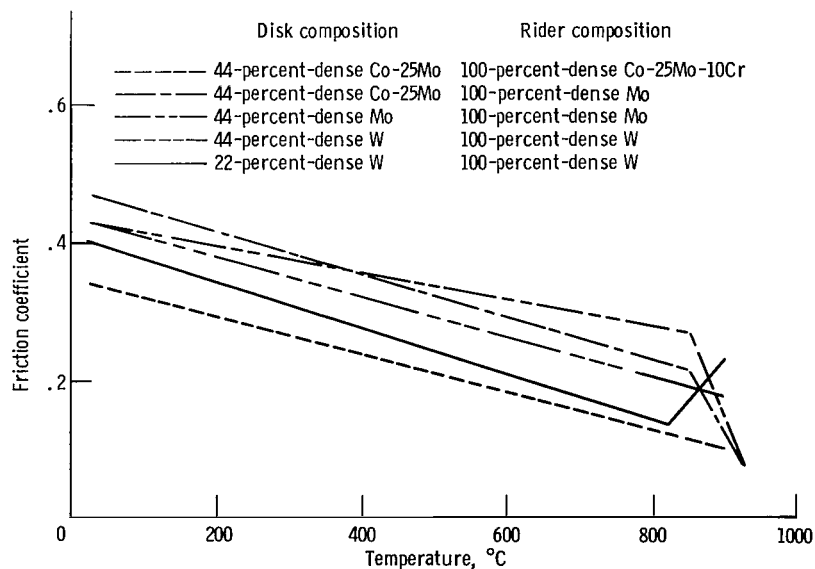


Figure 7. - Summary of mean friction coefficients as function of temperature for dense metal riders sliding on porous metal disks filled with  $38\text{CaF}_2$ - $62\text{BaF}_2$  eutectic. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

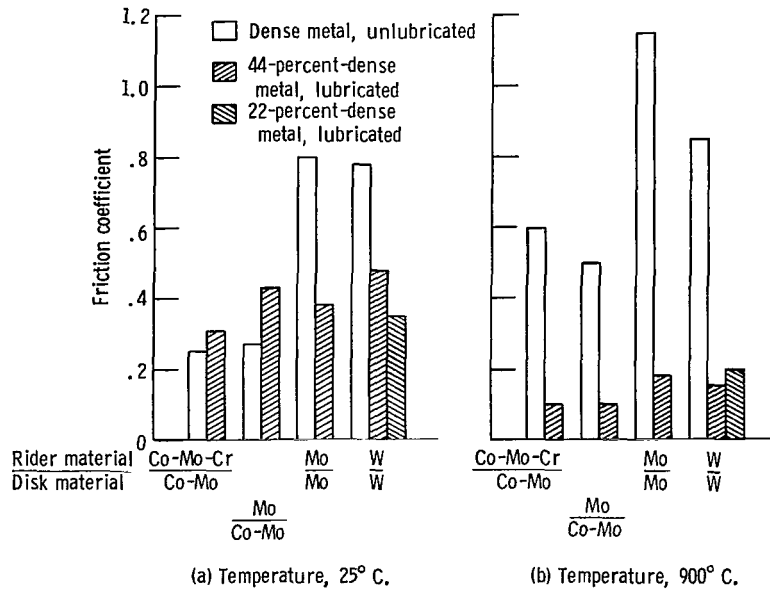


Figure 8. - Friction coefficients at 25° and 900° C of various porous metals filled with  $38\text{CaF}_2$ - $62\text{BaF}_2$  eutectic compared with similar dense metals. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

of the composites tested) is given in figure 7. In figure 8, a comparison of the mean friction coefficients for self-lubricating composites and dense metals is given at 25° and 900° C. The beneficial effect of the  $\text{CaF}_2$ - $\text{BaF}_2$  lubricant is much more pronounced at 900° C than at 25° C.

## Rider Wear Behavior

Once the frictional properties of the composites were determined, 1-hour tests at 25° and 900° C were conducted to determine the wear characteristics of the composite materials. The same conditions were adhered to as in the cyclic tests except that the duration of the tests was 1 hour at each desired temperature.

Similar tests were conducted using the dense, unlubricated materials. Since wear rates of the tungsten and molybdenum metals were very high, a test duration of only 2 minutes was employed for these metals. The assumption was made that the wear was linear with time and the wear per hour was calculated in order to make a direct comparison.

The wear data are given in figure 9. Here the wear rate for each material combination is plotted on a log scale. In every case, the wear of the rider is reduced when the composite disk material is used.

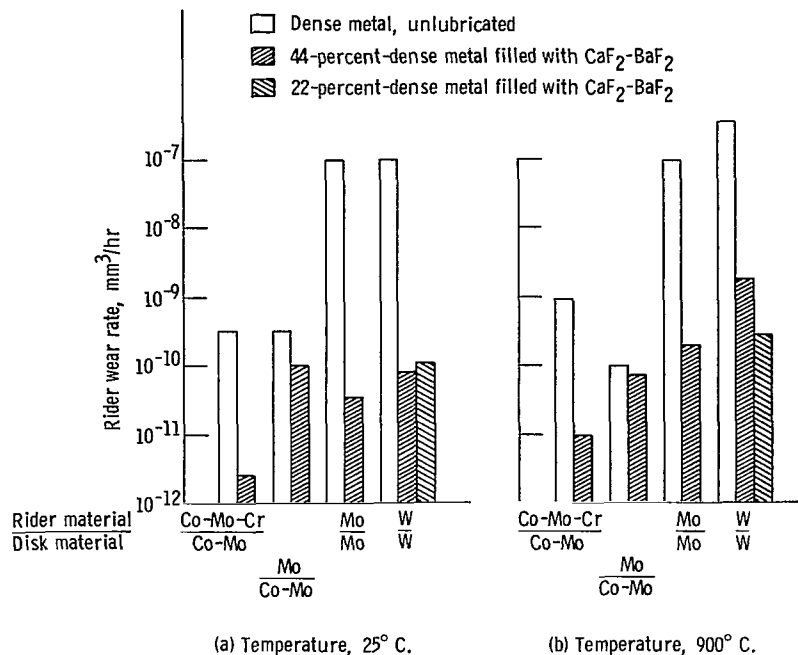


Figure 9. - Rider wear rates at 25° and 900° C of various porous metals filled with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic compared with similar dense metals. Sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture).

Co-25Mo-10Cr riders sliding on Co-25Mo composite disks gave the lowest wear rates both at 25° and 900° C. These wear rates are about two orders of magnitude lower than the dense-metal results. The Mo riders sliding on the Co-25Mo composite disks also gave improved wear resistance, but it was not nearly as good as that obtained with the Co-25Mo-10Cr riders.

Probably the best improvement in wear resistance, relative to the unlubricated metals, was achieved with Mo and W riders sliding in composite disks of these metals impregnated with the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic. The rider wear rates on these composites are less than one-thousandth the rider wear rates on the unlubricated metal disks. However, these wear rates are still an order of magnitude higher than those obtained for the Co-25Mo composites.

With one exception, the wear rates at 900° C are greater than the corresponding wear rates at 25° C. The exception is Mo sliding on a Co-25Mo composite disk. In this case the wear rates at 25° and 900° C are about equal.

Since wear inhibition is usually the most important criterion when sliding contact is involved, the low wear of the Co-25Mo composite at room temperature makes it the most promising wear-resistant material (of those tested) for use at both high and low temperatures.

## Photographic Comparison

A photographic comparison of representative rider and disk wear scars after 1 hour tests at 25° C is given in figure 10. A similar comparison at 900° C is shown in figure 11. In agreement with the wear rates given in the previous figures, these photographs show that the least wear occurs with Co-25Mo-10Cr riders sliding on Co-25Mo composite disks. It also appears that the least material transfer takes place with the Co-25Mo-10Cr rider - Co-25Mo composite disk combination.

The most material transfer occurred at 900° C when Mo riders were used (figs. 11(b) and (c)) or when 22-percent-dense tungsten disks were used (fig. 11(e)). When Mo slid on the 44-percent-dense Co-25Mo composite, the transferred film consisted primarily of  $\text{CaF}_2$ - $\text{BaF}_2$  eutectic lubricant (fig. 11(b)).

With Mo sliding on Mo composites and W sliding on 22-percent-dense W composites, the transferred film consisted of a combination of lubricant and metallic wear debris (figs. 11(c) and (e)). The wear scars on the tungsten riders sliding on the 22-percent-dense tungsten disks are elliptical in shape (figs. 10(e) and 11(e)). This indicates that the composite was not strong enough to support the load, and a plowing action on the disk took place until the area of contact was large enough to support the load.

## Disk Wear Behavior

Representative surface profiles of the wear tracks on the 44-percent-dense composite metal disks are shown in figure 12. They were taken after each 1-hour test was completed. The figure shows that the least wear occurs to the Co-25Mo disks in contact with either a Co-25Mo-10Cr rider or a Mo rider. The type of rider material did not seem to influence the disk wear.

The molybdenum and tungsten composite disks wore much more than the Co-25Mo composite disks, with the wear of tungsten being the most severe. In none of these cases did wear seem especially sensitive to temperature. The wear at 25° and 900° C for each specific material combination was about the same. No radical differences were observed.

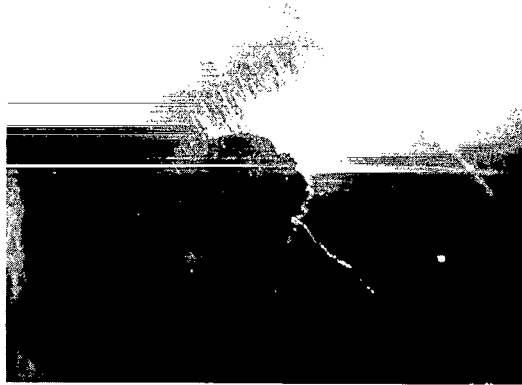
Representative surface profiles of the wear tracks which occurred on the 22-percent-dense tungsten composites are shown in figure 13. These are given for specimens tested at 25° and 900° C. The figure illustrates that the wear of the 22-percent-dense tungsten composite disks is quite extensive compared to the 44-percent-dense tungsten composite disks.



Disk wear tracks



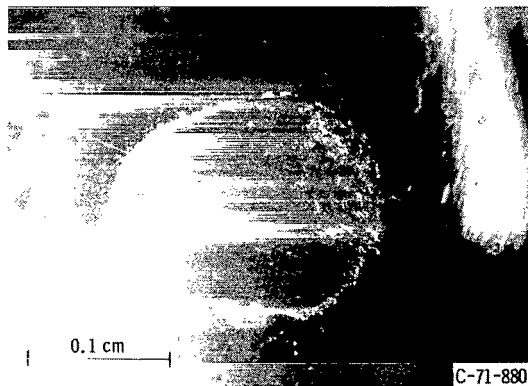
Rider wear scars



(a) Co-25Mo-10Cr rider sliding on 44-percent-dense Co-25Mo disk.



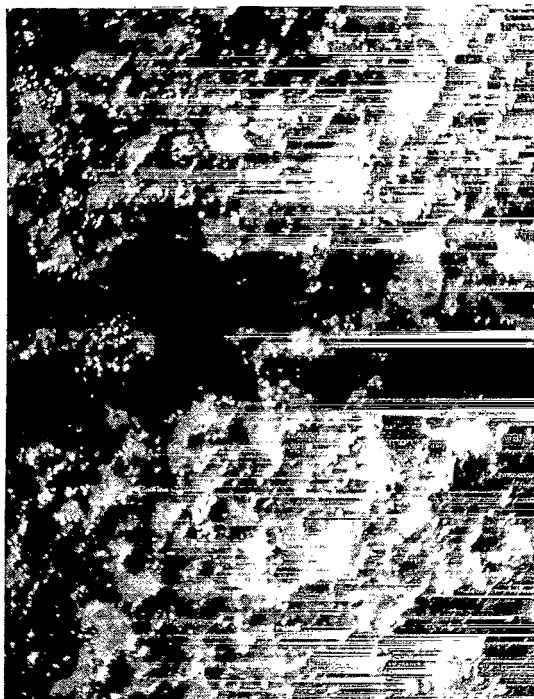
(b) Molybdenum rider sliding on 44-percent-dense Co-25Mo disk.



(c) Molybdenum rider sliding on 44-percent-dense molybdenum disk.

Figure 10. - Representative wear scars from friction and wear tests conducted at 25° C using porous metal disks filled with  $^{38}\text{CaF}_2$ - $^{62}\text{BaF}_2$  eutectic.

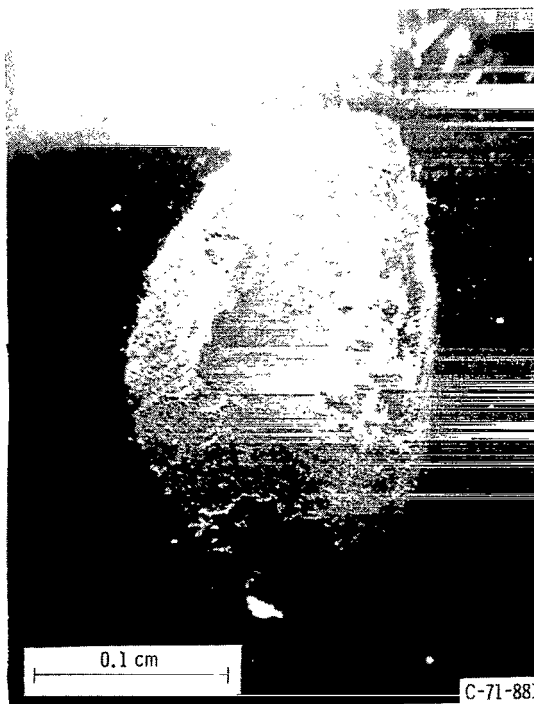
Disk wear tracks



Rider wear scars



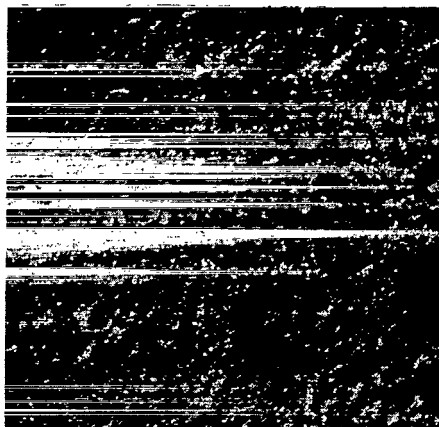
(d) Tungsten rider sliding on 44-percent-dense tungsten disk.



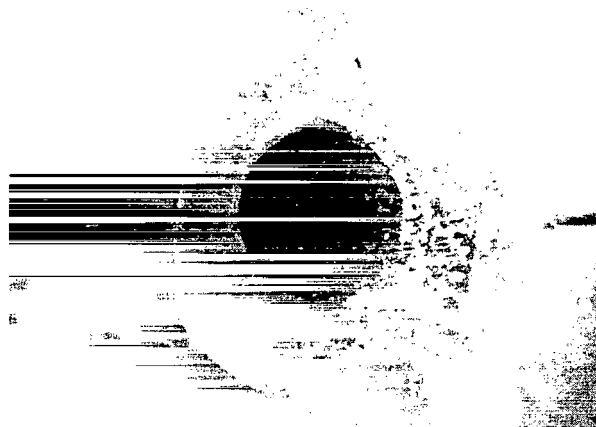
(e) Tungsten rider sliding on 22-percent-dense tungsten disk.

Figure 10. - Concluded.

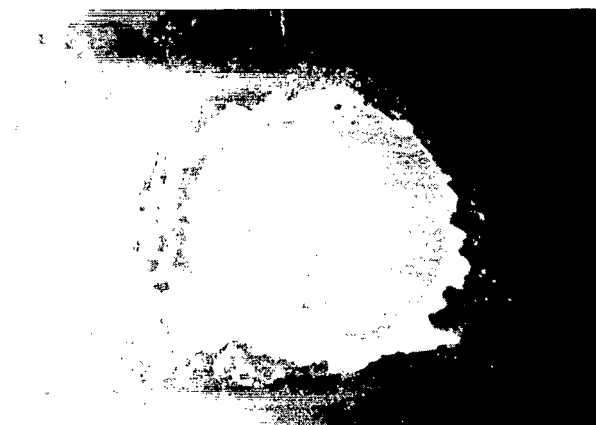
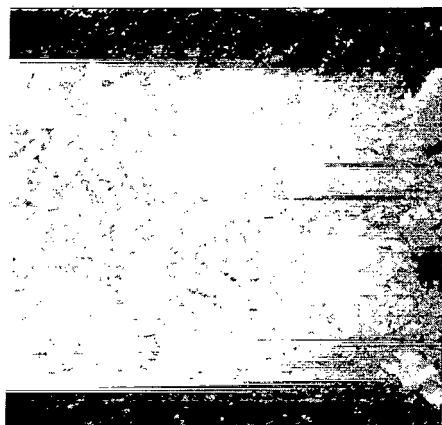
Disk wear tracks



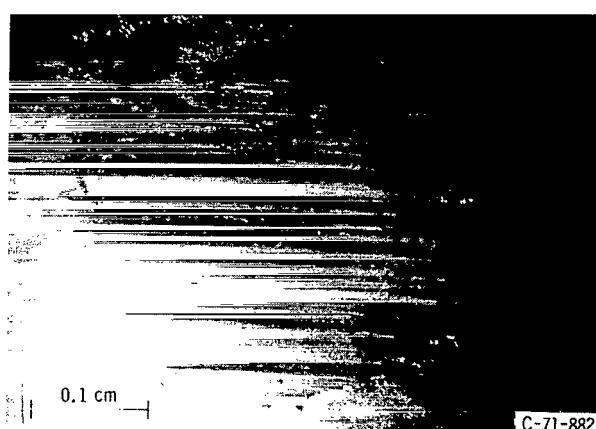
Rider wear scars



(a) Co-25Mo-10Cr rider sliding on 44-percent-dense Co-25Mo disk.



(b) Molybdenum rider sliding on 44-percent-dense Co-25Mo disk.



(c) Molybdenum rider sliding on 44-percent-dense molybdenum disk.

Figure 11. - Representative wear scars from friction and wear tests conducted at 900° C using porous metal disks filled with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic.

Disk wear tracks



Rider wear scars



(d) Tungsten rider sliding on 44-percent-dense tungsten disk.



(e) Tungsten rider sliding on 22-percent-dense tungsten disk.

Figure 11. - Concluded.

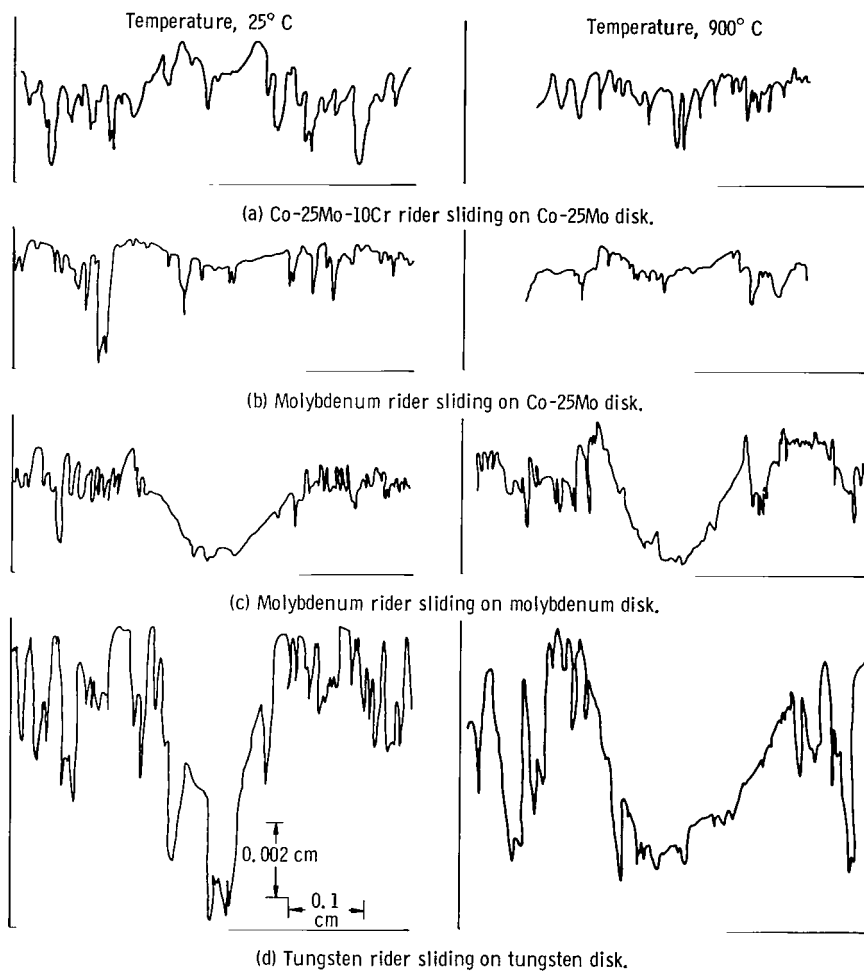


Figure 12. - Representative surface profiles at 25° and 900° C of wear tracks on 44-percent-dense metal disks filled with  $38\text{CaF}_2$ -62 $\text{BaF}_2$  eutectic. Track diameter, 5 centimeters; sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture); duration of test, 1 hour. (Vertical magnification is 50 times horizontal in these surfaces profiles.)

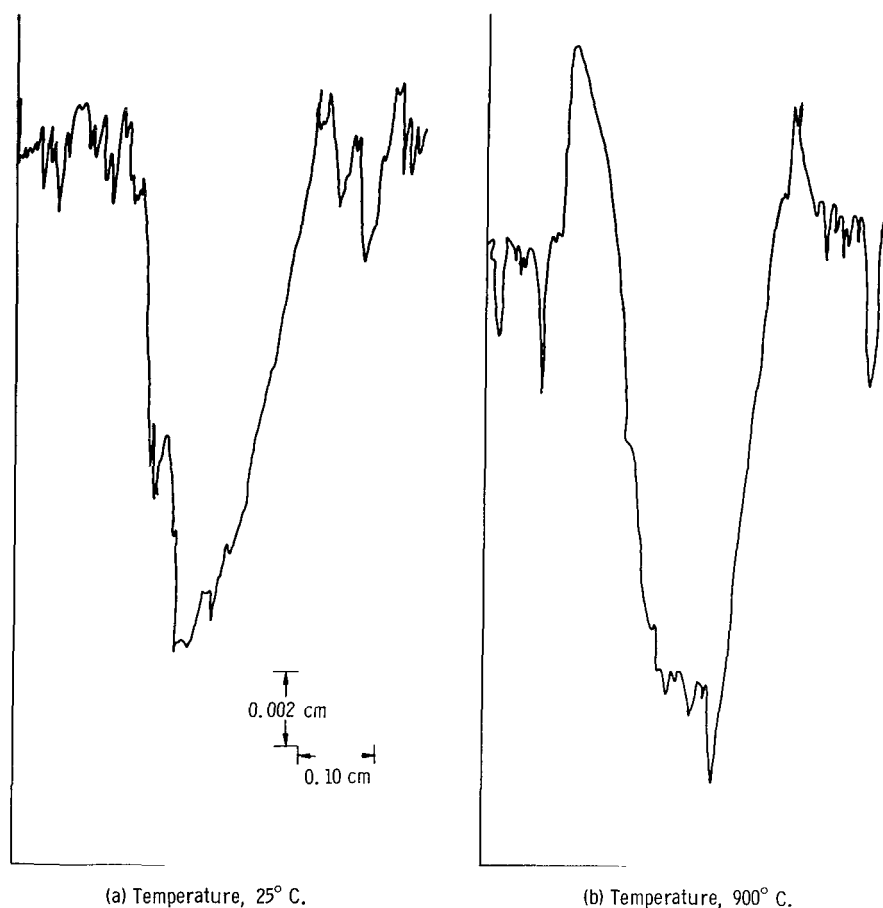


Figure 13. - Representative surface profiles at 25° and 900° C of wear tracks on 22-percent-dense tungsten disks filled with 38CaF<sub>2</sub>-62BaF<sub>2</sub> eutectic. Track diameter, 5 centimeters; sliding velocity, 2.6 meters per second; load, 1 kilogram; dry argon atmosphere (10 ppm moisture); duration of test, 1 hour. (Vertical magnification is 50 times horizontal in these surface profiles.)

## SUMMARY OF RESULTS

Experiments conducted in an argon atmosphere on self-lubricating composites made of porous metal disks infiltrated with a 38-weight-percent CaF<sub>2</sub> - 62-weight-percent BaF<sub>2</sub> eutectic composition yielded the following results:

1. A Co-25Mo sintered porous metal (44 percent dense) served as the best matrix material (of those tested) for the CaF<sub>2</sub>-BaF<sub>2</sub> eutectic lubricants. Better results were obtained with a 65Co-25Mo-10Cr rider than with a Mo rider.

2. The Co-25Mo and CaF<sub>2</sub>-BaF<sub>2</sub> eutectic in combination were of mutual benefit in providing a lower friction over a wider range of temperatures. The friction coefficient was 0.35 at room temperature and dropped off in a linear manner with increasing temperature to 0.10 at 900° C.

3. Molybdenum and tungsten also proved to be suitable matrix materials for

calcium-fluoride-based lubricants. Since these two metals have high melting points, they could serve as matrix materials for fluoride lubricants with higher melting points than the one used in this study.

4. The wear rates of riders sliding on the composite disks were three orders of magnitude less than the wear rates of riders sliding in equivalent tests on dense unlubricated metals.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, March 9, 1971,  
126-15.

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